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New Neutron Radiation Effects Capabilities at The Low Energy Neutron Source (LENS)

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Abstract

The Low Energy Neutron Source (LENS) is a novel, university-based pulsed neutron source located within the Center for Exploration of Energy and Matter (CEEM) at Indiana University. The source utilizes a low energy p-n reaction in Beryllium coupled with a high-current, variable-pulse-width proton accelerator to produce either short or long neutron pulses. One of the target stations has been optimized for neutron radiation effects studies of device and board level electronics testing with quasi monochromatic high flux neutron beams (~ 1 MeV equivalent silicon). The total neutron flux at the device under test (DUT) is approximately $2 \cdot 10^{10}$ $(n/cm^2/sec)$ with low gamma contamination, $1 \cdot 10^9$ $(n/cm^2/sec)$. The neutron spectrum at the DUT position has been calculated using MCNP-X and has been characterized using foil activation measurements. In this paper we will describe the physical arrangement of the Device Test Area and indicate the unique features that have been incorporated to enhance testing effectiveness. We will also present the results of MCNP-X calculations with various adsorbed reflector arrangements that modify the spectrum incident on the device. Validation of the MCNP-X calculations using foil activation measurements will also be presented.

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Keywords: radiation effects facility; MCNPX; foil activation; neuron spectrum; NREF

1. Introduction

The Neutron Radiation Effects Facility (NREF) at Indiana University is part of the Low Energy Neutron Source (LENS). The 13 MeV accelerator produces a neutron spectrum with an endpoint energy of 11 MeV at LENS.

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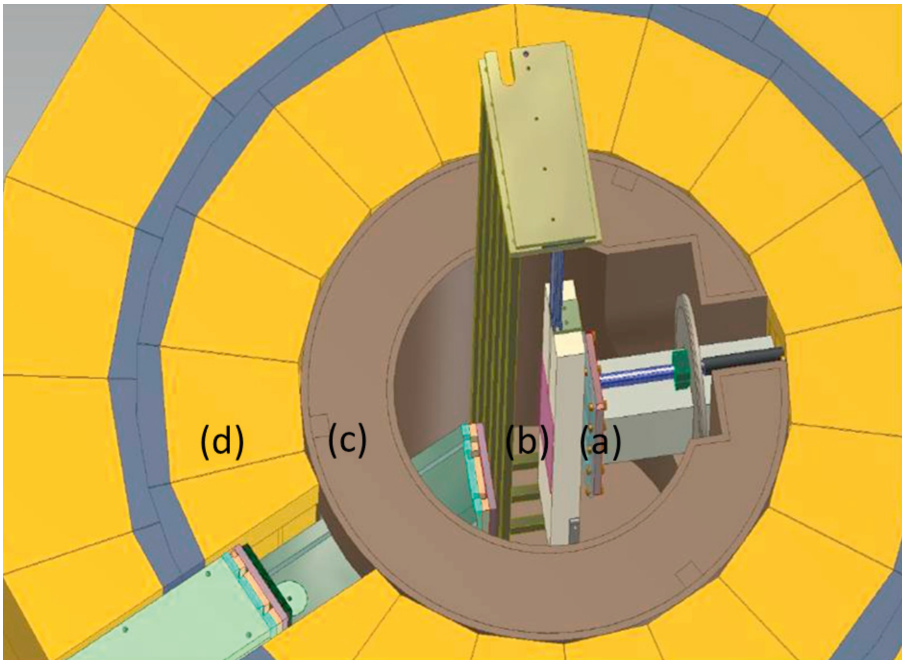


Fig. 1. The NREF target station layout at LENS: (a) the water cooled Be target, (b) the Device Under Test (DUT) area, (c) a lower lead shielding, and (d) an external shielding composed of the structure of polyethylene-lead wedges.

NREF has been constructed to accommodate device and board level electronics testing with quasi monochromatic high flux neutron beams. The neutron flux at the device under test (DUT) is approximately $2 \cdot 10^{10}$ $(n/cm^2/s)$ with 13 MeV, 20 mA, a repetition rate of 20 Hz and a 400 μs monochromatic square proton beam accelerator, and the low gamma contamination, $1 \cdot 10^9$ $(n/cm^2/s)$. The neutron spectrum can be easily modified through the addition of moderating materials. With moderating materials thermal neutron production is increased with a corresponding reduction in fast neutron production. The neutron spectrum at the DUT position has been calculated using MCNPX and verified using foil activation measurements. Both the calculated and experimental results have an acceptable error level and good agreement.

2. Testing area

LENS has two Target-Moderator Reflector (TMR) assemblies for neutron production. The proton beam can be directed to only one of these assemblies at a time. The radiation effects testing is carried out using TMR1 which has been specially configured for this purpose. TMR1 consists of the water cooled Be target, a Device Under Test (DUT) area, a lower lead shielding, and an external shielding composed of the structure of polyethylene-lead wedges. This is illustrated in Figure 1.

Device testing is conducted in the target station utilizing a mechanized carrier to lower parts into the neutron beam produced by protons on a beryllium target. Effective DUT area is 30 cm wide x 56 cm high x 14 cm deep as shown in Figure 2 (a). A mechanized carrier can be remotely lowered to DUT area by a mechanical control panel.

Provisions for device control cables to be connected to the part under test, if required, allow live testing and monitoring of the part. Inside the irradiation vault, 15 cm long cable is required where the neutron dose is approximately 10 mrem/hr. Outside the irradiation vault, a 5 m long cable is required where the neutron dose is approximately 1

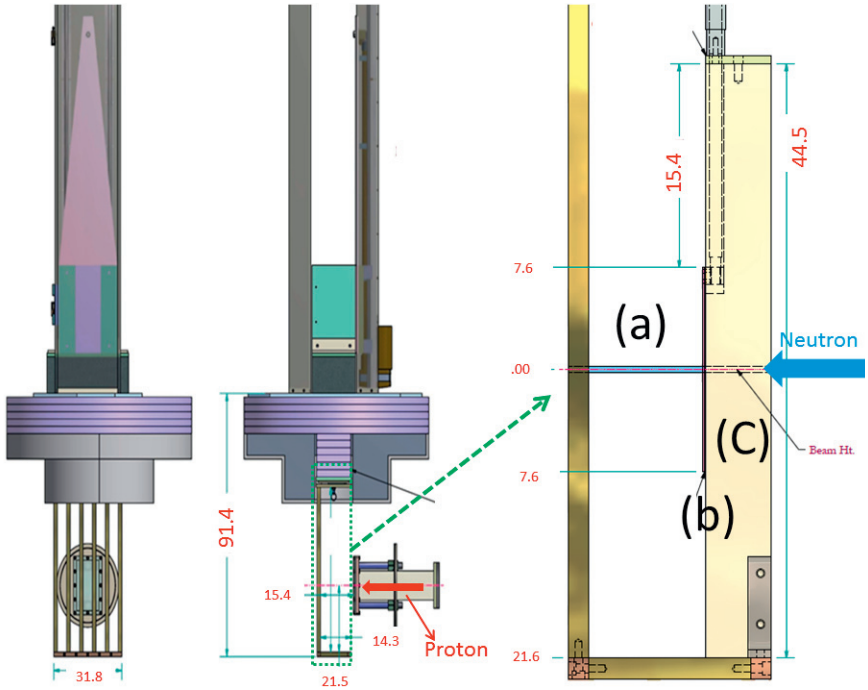


Fig. 2. The mechanized carrier in DUT: (a) 30cm wide 56cm high 14cm deep effective DUT area and (b) a remote controlled 1 mm thick Cadmium cover, and (C) a selective 5cm thick polyethylene moderation.

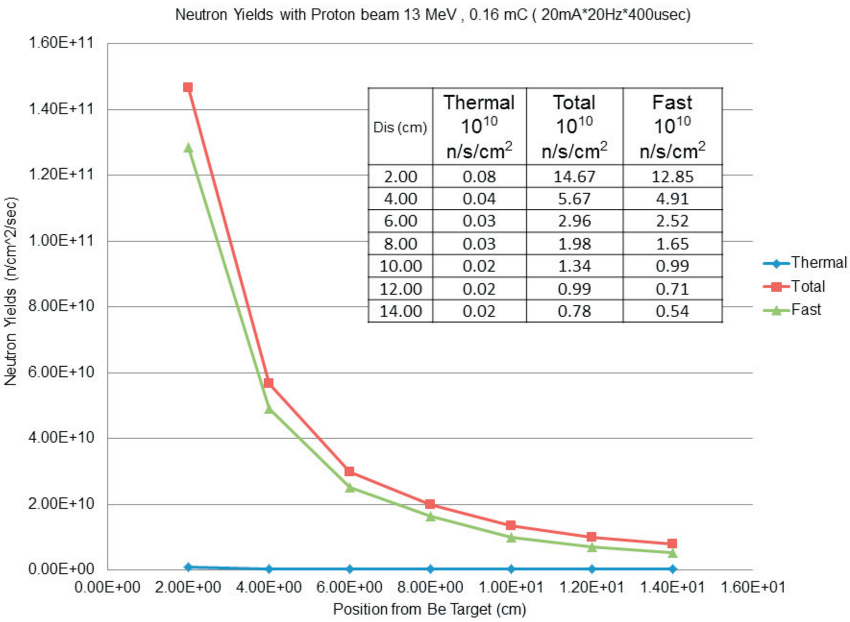
mrem/hr. In many radiation effects studies, the influence of thermal neutrons is inferred by measurements with and without Cadmium cover to eliminate the thermal neutrons incident on DUT. We have added a polyethylene moderator to produce the thermal neutrons as shown in Figure 2 (c) and also added a Cadmium cover that can be remotely inserted when desired in order to eliminate thermal neutrons as shown in Figure 2 (b).

3. Neutron Beam characterization

It is required not only to precisely characterize neutron beam properties in aspects of neutron dose rate and energy spectrum, but also to validate these properties with accurate measurement results within an acceptable error level in order to produce the reliable radiation testing results. A Monte Carlo N-Particle, X (MCNP-X) 2.7.0 model [LA-UR-03 (1987)] has been developed and the expected neutron spectrum is calculated using this model. Foil activation techniques are used to measure the neutron flux from the gamma activity and the measured neutron flux are compared and validated with calculated values.

3.1. Neutron spectrum calculations

CNP-X model has been developed to calculate the neutron spectrum at the DUT area in NREF. Each model has been run in 210 histories using the Indiana University Parallel Quarry computing system [Indiana University (2013)] and resulted in very small error levels (between 0.01 and 0.05 %). The calculated neutron spectrum at the various DUT positions from Beryllium target is shown in Figure 3.



Dis (cm)	Thermal 10^{10} n/s/cm^2	Total 10^{10} n/s/cm^2	Fast 10^{10} n/s/cm^2
2.00	0.08	14.67	12.85
4.00	0.04	5.67	4.91
6.00	0.03	2.96	2.52
8.00	0.03	1.98	1.65
10.00	0.02	1.34	0.99
12.00	0.02	0.99	0.71
14.00	0.02	0.78	0.54

Fig. 3. The neutron spectrum at the various DUT positions with 13 MeV, 20 mA, a repetition rate of 20 Hz, and a 400 s wide proton beam.

Without any moderation materials only fast neutrons with energies above 0.1 MeV are generated and neutron flux are decreased exponentially as DUT area is far from the neutron source. Figure 4 shows the neutron spectrum with 5cm thick polyethylene moderation. Thermal neutrons with energies blow 1eV are generated along with decreasing the fast neutron flux.

Typical DUT area (at 8 cm from the target) calculation is presented in Figure 5. The fast neutrons are mainly produced without moderation: intensities are approximately $1.5 \cdot 10^{10}$ $(n/cm^2/s)$ and the thermal neutrons are produced with 5 cm thick polyethylene moderation: Intensities are approximately $0.5 \cdot 10^{10}$ $(n/cm^2/s)$. The spatial distribution at typical DUT position is also calculated and shows the monochromatic distribution around the proton beam size (approximately 5cm diameter) as shown in Figure 5 and Figure 6 respectively.

3.2. Foil activation measurement

The incident neutron fluence at DUT can be calculated by measuring the specific activities of the activated foils and pallets as follows:

$$f = \int_0^\infty \Phi(E')dE', \quad \overline{\sigma}_{mat} = \frac{\int_0^\infty \Phi(E')\overline{\sigma}_{mat}(E')dE'}{f}, \quad f = \frac{A_\infty}{N\overline{\sigma}_{mat}} \tag{1}$$

Where f is neutron fluence, $\Phi(E')$ is incident neutron energy-fluence at energy E', σ_{mat} is effective neutron cross section, $\sigma_{Mat}(E')$ is the neutron cross section at each energy E', N is number of atoms in each material and A_∞ is the measured specific activity of the activated foil. The incident neutron energy-fluence spectrum at energy $\Phi(E')$ is calculated by using a computer code MCNP-X. A specific activity after irradiation is given as follows [Knoll (200)]:

$$A_\infty = \frac{\lambda(C - B)}{\epsilon(1 - e^{-\lambda t_0})e^{-\lambda t_0}(e^{-\lambda t_1} - e^{-\lambda t_2})} \tag{2}$$

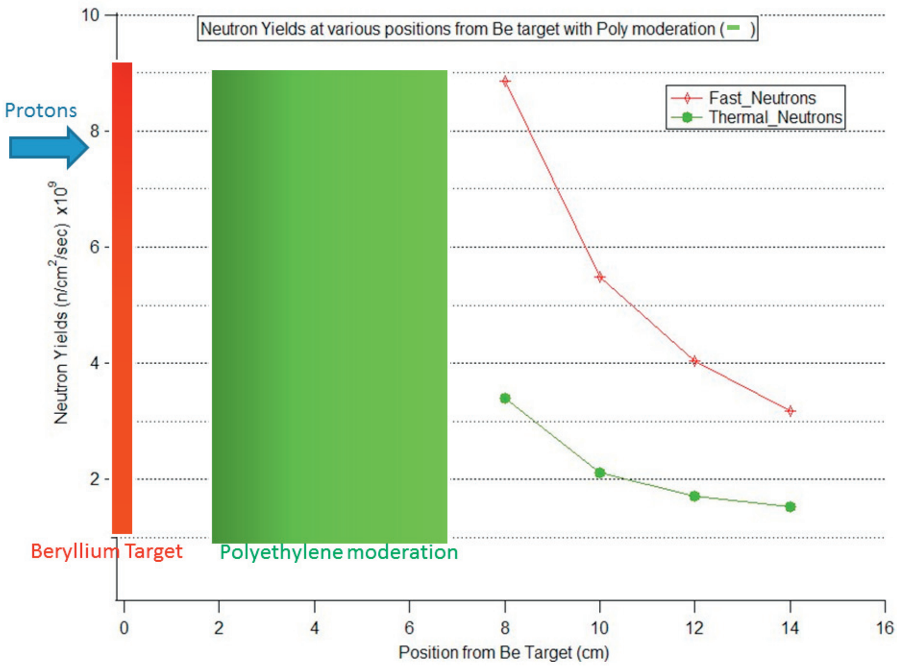


Fig. 4. The neutron spectrum with 5cm thick polyethylene moderation.

Where λ is decay constant (=ln2/ half-life time), C is number of counts, B is number of background counts, ϵ is overall counting efficiency at each energy region, t_0 is irradiation period, $t_0 - t_1$ is waiting period and $t_1 - t_2$ is counting period. Gold, and Zinc foils were used to measure the thermal flux, i.e. neutrons with energies up to 1 eV, since these foils have much larger neutron cross section resulted in higher reaction rate in the thermal energy region. Iron foils and Sulphur pellets were used to measure the fast neutron flux with energies above 0.1 MeV. This separation of applying the thermal and fast neutron foils depending on neutron cross section and reaction rate makes error levels lower than those in the previous results [Halstead et al. (2012)]. A high purity Canberra GC2020 Germanium Detector is used for gamma-ray detection and the scintillator detector is used for X-ray detection. Table 1 shows the comparison between measured and calculated flux at typical DUT (at 8 cm from the target).

Table 1. Comparison between the measured and calculated flux

An example of a column heading	Column A (t)	Column B (t)
	Measured $10^{10}\ n/s/cm^2$	MCNP-X $10^{10} n/s/cm^2$
Fast, > ~ 0.1 MeV, Fe, S	1.25+/-.05	1.65
Thermal, < 1 eV, Cu,Au, Zn	0.32+/-.01	0.34

Fast and thermal neutron flux measurements depending on sample positions from the target are shown in Figure 7 and Figure 8 respectively. The measured intensities are approximately 10 ~ 20 % lower than calculated values and have an acceptable error level: approximately from 0.1 to 0.5 %

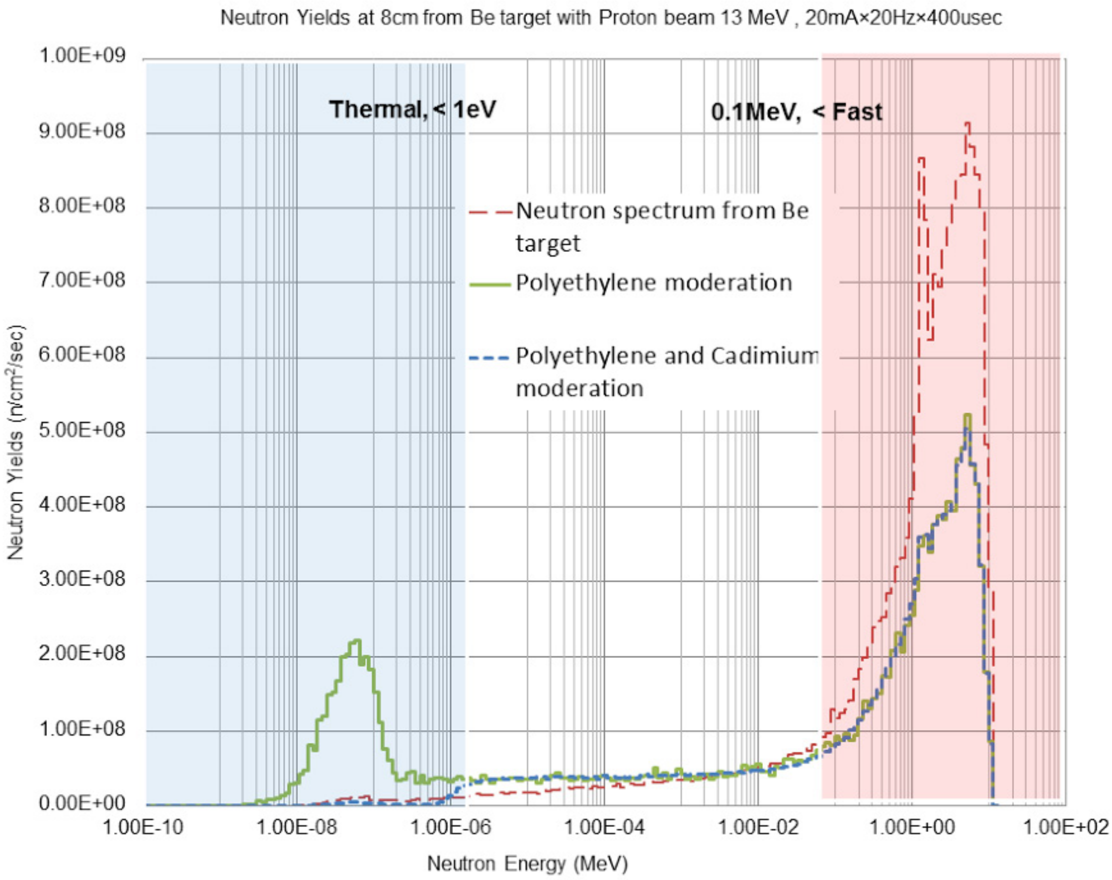


Fig. 5. The neutron spectrum at typical DUT area (at 8 cm from the target).

4. Conclusion

Device and board level testing area has been successfully assembled and validated in NREF at Indiana University. Neutron beam characterization has been accomplished with MCNP-X code calculations and foil activation measurements. The 1-MeV equivalent neutron fluence for the silicon at a typical DUT is approximately $2 \cdot 10^{10}$ $(n/cm^2/s)$. Measured intensities are approximately 10 ∼ 20% lower than calculated intensities and have acceptable error levels, approximately from 1% to 5% error. NREF provides the selectable thermal and fast neutrons with easy modification of moderation materials and the flexible neutron flux with modification of proton beam power to suit the applications of users.

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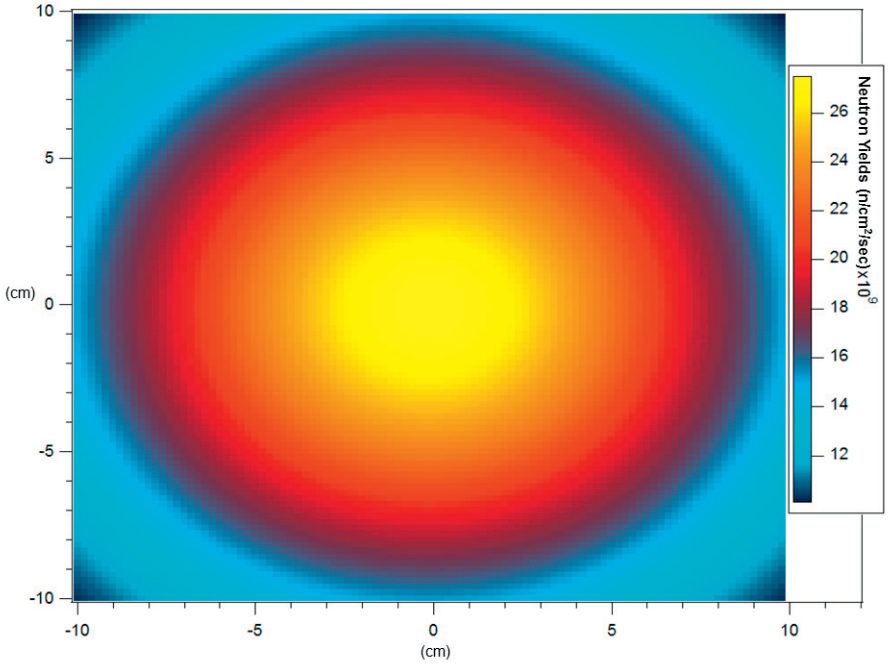

Fig. 6. The monochromatic spatial neutron distribution around the proton beam size (approximately 5cm diameter).

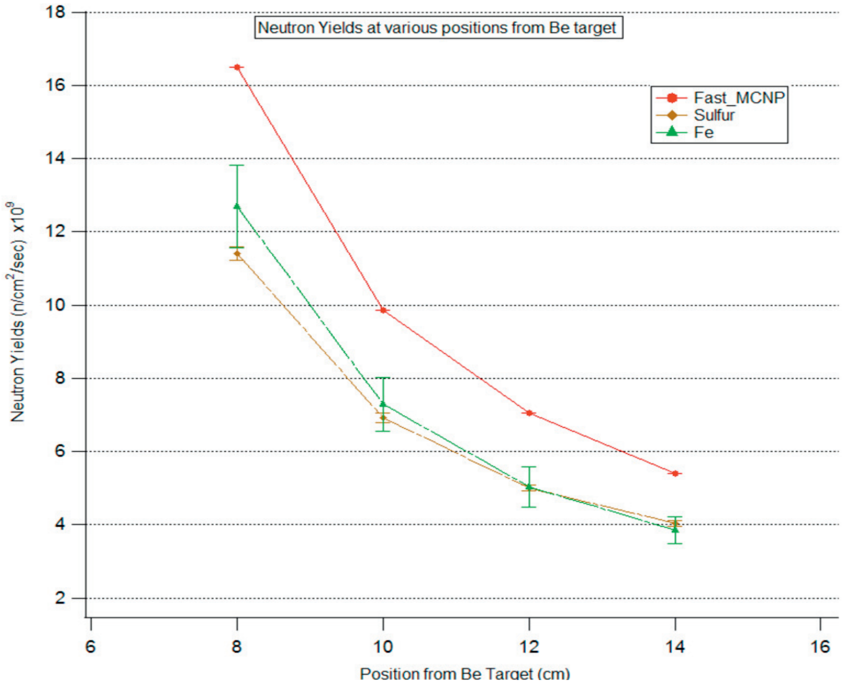

Fig. 7. The fast neutron flux measurement depending on sample positions from the target.

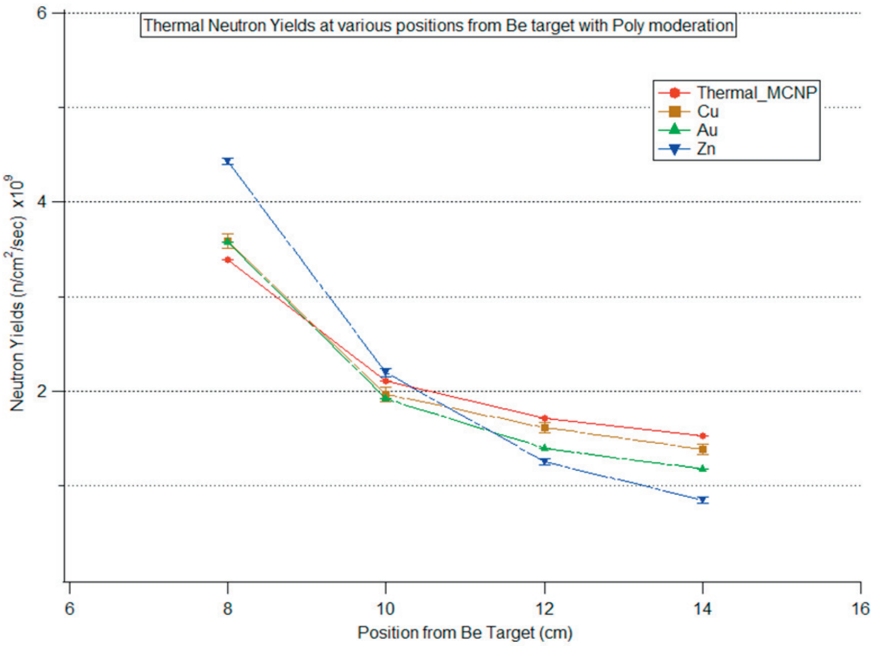

Fig. 8. The thermal neutron flux measurement depending on sample positions from the target.